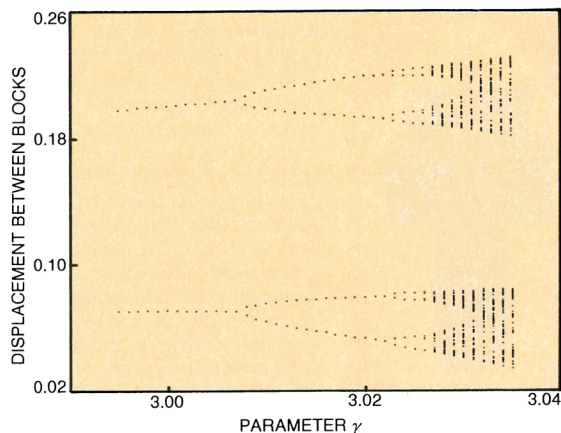


rate- and state-variable friction). The parametrization of the friction force in Ruina's model was based largely on the experimental measurements of James Dieterich (US Geological Survey, Menlo Park, California). With Jeffrey Nussbaum (now at General Electric) Ruina decided in 1987 to explore the consequences of the simplest possible model to see whether the dynamics alone rather than fault heterogeneities could produce spatially asymmetric behavior.⁶ The answer was yes. Nussbaum and Ruina's model consisted of two identical blocks, both subject to a friction force that switched between two possible values, dynamic and static, as the blocks first slid and then stuck. They found that the motion of the blocks was periodic, but generally not symmetric. In some solutions one block would always move in quicker slips than the other, while in other modes the two blocks would alternately undergo short slips.

In a more recent paper, Ruina and Frank Horowitz (now at Northwestern University) analyze a model with rate- and state-variable friction that is homogeneous in its material properties and has no effects from the ends of a chain.⁷ It is essentially a continuum model with the slip varying continuously along the fault. Again they find that the dynamics can generate both temporal and spatial complexity in seismic phenomena.

This year Jie Huang and Donald Turcotte adopted⁸ essentially the same model as Nussbaum and Ruina, but they allowed the friction force acting on one block to be larger than that on the second by a factor β . With this asymmetry, Huang and Turcotte produce evidence for deterministically chaotic behavior. For their analysis they first displayed the successive states of their system in phase space,



plotting the position of one block versus the other. The evolving trajectory never settled down to one or a finite number of points, as one would expect if the system approached either steady-state or periodic behavior. Rather, it filled the phase-space plot. Moreover, the system appeared to follow a period-doubling route to chaos: As a parameter γ , which describes the variation of friction with velocity, was increased, the system evolved first toward a single phase-space point; then, as the parameter continued to increase, the system oscillated between two final states, then four states, then eight and so forth.⁹ (See the figure above.)

Turcotte told us that they have now calculated a positive value for the Lyapunov exponent for a model in which the friction becomes smaller as the block moves faster. (The Lyapunov exponent is a measure of the rate of exponential divergence of two points of the system in phase space that start out arbitrarily close to each other.) This work demonstrates chaos only for a system of two blocks and

Period doubling in the behavior of two elastically coupled blocks with equal masses but subject to different friction forces.⁹ The graph plots the displacement between the two blocks at the end of a slip as a function of a system parameter γ . As γ increases, the system tends toward two phase-space points, then four and so forth.

—BARBARA GOSS LEVI

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HUBBLE INVESTIGATION BOARD FINDS OUT WHAT WENT WRONG

By what sequence of mishaps did the Hubble Space Telescope acquire its unfortunate spherical aberration? And how did this severe optical flaw escape notice until after the HST was launched into orbit last spring? These were the two principal questions set out for the HST Optical Systems Board of Investigation convened by NASA at the end of June, shortly after it became clear that the Hubble telescope was hobbled by half a wavelength of spherical aberration. (See *PHYSICS TODAY*, August, page 17.)

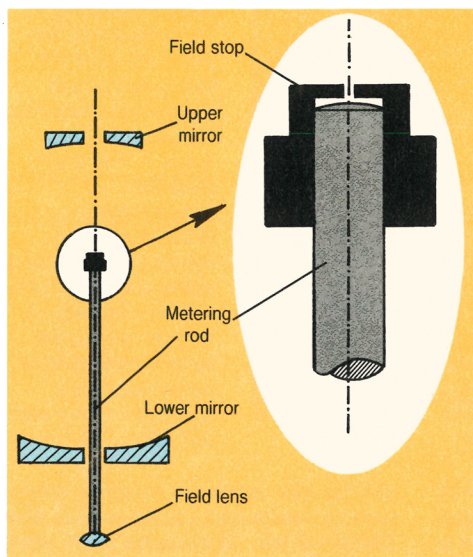
In less than three months the

board, headed by Lew Allen, director of the Jet Propulsion Laboratory, came up with a surprisingly complete answer to the first of these questions. The Allen board's answer to the second question, more fraught with touchy issues of administrative responsibility, is expected with the release of its full report sometime this month.

The other members of the board are Roger Angel and Robert Shannon (both at the University of Arizona), Charles Spoolhof (retired from Kodak), George Rodney (NASA head-

quarters) and John Mangus (Goddard Space Flight Center).

On 13 September, after the board's third meeting at Hughes Danbury Optical Systems (formerly Perkin-Elmer) in Danbury, Connecticut, where the Hubble's great primary mirror had been painstakingly polished to its final figure a decade ago, Allen released a statement outlining the circumstances that resulted in the crucial fault in the optical template that guided, or rather misguided, the careful polishing of the mirror. "The board is confident," he wrote, "that



Reflective null corrector used to monitor the polishing of the Hubble's primary mirror to its desired hyperbolic shape. It consists of two small spherical mirrors half a meter apart and a field lens about 15 cm below the bottom mirror's aperture. The metering rod used to position the field lens is also shown. The insert shows the reflecting domed top of the rod, masked by a field stop with a tiny aperture and nonreflective painted surface. The 1.3 mm vertical distance between the top of the rod and the top of the field stop is precisely the spacing error in the position of the field lens relative to the lower mirror of the null corrector.

most, if not all, of the [Hubble's optical] problem can be traced to a spacing error in the reflective null corrector, an optical reference device used in the manufacture of the primary mirror. . . . The board is fairly confident that it has [also] identified how the mistake occurred."

The null corrector

The reflective null corrector is the optical template used to monitor the final polishing of the 2.4-meter-diameter primary mirror. If one simply wanted a concave spherical mirror, one would only have to place a point light source at the desired center of curvature and keep polishing until the surface reflected all the light precisely back to the source. But the Ritchey-Chrétien Cassegrainian design of the Hubble telescope requires that the mirror surface be a hyperboloid of revolution—a much more demanding proposition.

By interposing a small, carefully fabricated optical complex—the null corrector—between the monitoring light source and the uncompleted mirror, one can, however, modify the optics so that the light rays would strike all parts of the correct hyperbolic surface precisely at right angles. Thus one would know that the primary mirror had finally reached its proper shape when all the reflected light returned exactly to the monitoring point source.

The null corrector used to finish the primary mirror at Perkin-Elmer in 1980 looks something like a miniature Gregorian telescope: two small concave mirrors facing one another, each with a hole at its center, and a field lens below the bottom hole. If the

optical parameters of the three components, and the spacings between them, are precisely right, laser light from a source above the top mirror will bounce around inside the null corrector and emerge through the field lens heading for all parts of the primary mirror below with its propagation direction everywhere normal to the desired hyperbolic shape. When the primary reflects the light back up through the null corrector, an interferometer just below the light source compares the outgoing and returning beams. An interference pattern indicating that the returning light has exactly retraced its steps to the focus should be the signature that the Hubble primary mirror's shape is right.

The wrong spacing

We know, of course, that the primary mirror's shape is wrong. The problem, it turns out, was in the spacing inside the null corrector. Surprisingly, in the decade since the completion of the Hubble mirrors, the null corrector had not been moved or altered. Everything was in place. Thus the Allen board was able to determine in mid-August that the field lens was 1.3 mm too far below the bottom mirror of the null corrector. That spacing error, the board calculated, is enough to account fully for the magnitude and sign of the spherical aberration deduced from the images sent back by the orbiting Hubble telescope. Knowing this much should ease the task of designing the corrective optics NASA plans to send up to the Hubble in 1993.

The next question for the board to answer was: How did the spacing

error come to be? The investigation, Allen wrote on 13 September, "has been greatly facilitated by the fact that almost all the hardware involved in fabricating the primary mirror was available for examination and analysis by the board." They had access not only to the null corrector but also to the instruments used in the careful spacing of its components. Robert Parks (University of Arizona), the board's representative at Hughes Danbury, was able to interview many of the present and former employees who had participated in the fabrication of the null corrector. Together they seem to have succeeded in reconstructing for the board just what went wrong.

When the reflective null corrector was put together ten years ago, a metering rod was fabricated with a length precisely equal to the desired distance from the center of curvature of the lower mirror to the top surface of the field lens below. The rod was then threaded through the hole in the lower mirror, with its bottom end touching the lens. The goal was to adjust the vertical position of the rod and lens until the top of the rod was exactly at the lower mirror's center of curvature.

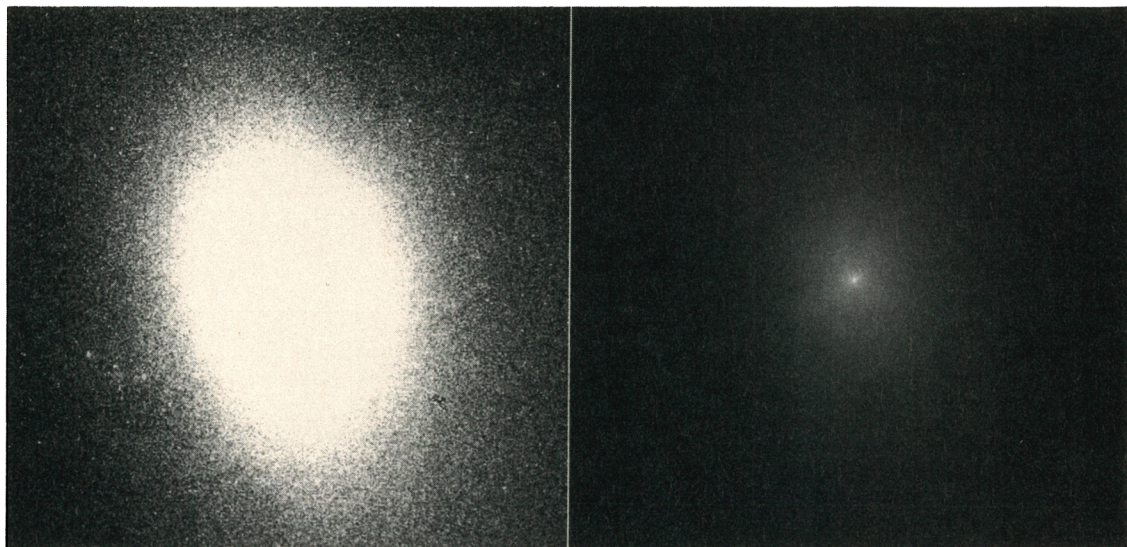
The precise positioning of the rod was to be done by interferometric rather than mechanical means, in order to achieve the required tolerance of 1 micron. Perkin-Elmer had considerable experience with this kind of sophisticated optical positioning. A small spherical-wave interferometry module (a "SWIM"), with its own laser light source and microscope objective, was positioned in the cavity between the null corrector's mirrors so that it focused the laser light precisely at the lower mirror's center of curvature (from above). The top of the rod had a reflecting spherical dome. (See the figure on this page.)

The trick now was to move the rod up slowly until its top rested exactly at the focal point of the SWIM beam. The interference pattern produced by the laser light reflected from the end of the rod back up through the microscope objective would tell the technician when the rod reached the focal point.

The wrong reflection

At this point a precaution was taken that proved to be unfortunate. To make sure that they would be looking only at light reflected from the very top of the rod's spherical dome, the Perkin-Elmer team put a mask (the so-called field stop) over the top of the rod, with a tiny hole in its center that would pass only light reflected from

Hubble Finds Surprisingly Dense Galactic Core



The Wide Field and Planetary Camera aboard the Hubble Telescope has sent back an intriguing picture of the central region of NGC 7457, a seemingly ordinary S0 galaxy some 40 million light years away. Both pictures shown here are representations of a single ccd image of the galaxy. Both show precisely the same field, with the same magnification. They differ only in the grey scales chosen to represent the contrast digitally recorded by the camera's ccd array.

The surprise shows up in the representation on the right, whose grey scale is chosen to provide optimal differentiation near the galaxy's core. The central pinpoint of brightness is only 0.13 arcseconds wide (fwhm). The resolution of the image, despite Hubble's spherical aberration, is 0.06 arcsec.

Such a concentrated central core has never before been seen, except in a few extraordinary galaxies much closer

than NGC 7457. These data tell us that the galaxy's peak luminosity density exceeds 2×10^4 suns/pc³, at least 100 times greater than expected. We know of only one galaxy with a higher peak luminosity—the extraordinary elliptical galaxy M 32, a companion of Andromeda that can be studied in great detail by Earthbound telescopes because it is only 2 million light years away.

"This extraordinary concentration of stars in the core of NGC 7457 was quite unexpected," says Tod Lauer (National Optical Astronomy Observatories, Tucson, Arizona). "We picked it for testing our capabilities because it seemed such an ordinary galaxy. Perhaps this sort of enormous central density is much more common than ground-based observation had led us to believe." The Hubble telescope will look for others.

—BERTRAM SCHWARZSCHILD

the very top of the rod. As a further precaution they painted the field stop with nonreflecting paint.

Now two otherwise trivial imperfections conspired to degrade this measurement from micron precision to millimeter error. First of all, the process of drilling the small aperture in the field stop caused a few bits of paint to chip off the edge of the hole, leaving shiny bald spots. Secondly, the top end of this particular metering rod was not quite as strongly rounded as the others with which the optical technician had prior experience. Therefore the field stop sat higher above the rod end than usual, with the consequence that the light reflected back into the microscope made a smaller spot than the technician was accustomed to see. So he looked around for a healthier spot of light, and what he finally settled on—sad to say—was the reflection from one of the bald spots on top of the field

stop, which sat 1.3 mm above the top of the measuring rod. Thus, the board believes, did the rod, and consequently the field lens, end up 1.3 mm too low.

"No one blames the optical technician," says board member Angel. "Mistakes like this are inevitable. What was missing was a recognition of the need to keep checking for errors. The responsibility must rest at higher echelons." But that is a subject for the board's final report.

The other null corrector

There is, in fact, another, earlier null corrector that plays a role in this tale of woe. The original coarse polishing of the primary Hubble mirror was done at Perkin-Elmer's Wilton, Connecticut, facility. The optical template used at Wilton was a *refractive* null corrector, with lenses rather than mirrors doing most of the work.

We now know that the refractive

null corrector was properly made. But when the two correctors gave contradictory indications a decade ago, the Perkin-Elmer people wrongly attributed the fault to the refractive null corrector, arguing that it had a less reliable pedigree than the reflective null corrector they had so carefully assembled at Danbury.

When the final polishing was finished, the old refractive instrument from Wilton was brought in to check the radius of curvature at the primary mirror's center. The interferograms from that final measurement were still available for the Allen board ten years later. "They show precisely the aberration we found after the Hubble was launched," Angel told us. But at the time, they were blamed on the supposed inaccuracy of the old refractive null corrector and not brought to the attention of the senior scientists.

—BERTRAM SCHWARZSCHILD ■